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FATIGUE CRACK RETARDATION
FOLLOWING A SINGLE OVERLOAD

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FOREWORD

This report is the result of an in-house effort under Project 1467, "Analysis Methods for Military Flight Vehicle Structures," Work Unit 13470413, "Experimental Studies in Fatigue Crack Propagation in USAF Aerospace Structures." The work was conducted by Capt. Terry D. Gray, Aerospace Engineer, Fatigue and Fracture Group, Solid Mechanics Branch, Structures Division, Air Force Flight Dynamics Laboratory. Mr. H. A. Wood is the Technical Manager of the Fatigue and Fracture Group.

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This Technical Memorandum has been reviewed and is approved.

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ABSTRACT

This report proposes a modification to the Wheeler fatigue crack retardation model. The modified model is derived and then used to predict existing data for the number of delay cycles following a single overload in 2024-T3 Aluminum, 4340 Steel, and Ti-6Al-4V Titanium alloy. All predictions were within essentially a factor of two of the experimental data.

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SYMBOLS

Δa - current crack growth increment since overload

C, n - crack growth rate constants

da/dN - crack growth rate

K_{max} - maximum stress intensity

K_{min} - minimum stress intensity

K_{OL} - overload stress intensity

ΔK - stress intensity range $(K_{max} - K_{min})$

ΔK_{eff} - effective stress intensity range

ΔK_{th} - threshold stress intensity range

m - Wheeler shaping exponent

N_d - observed delay cycles

N_p - predicted delay cycles

R - K_{min}/K_{max}

S - crack arrest factor

z_{OL} - overload interaction zone

σ_{ys} - yield stress

I INTRODUCTION

The qualitative effect of an overload on a fatigue crack propagating at some lower, cyclic load is well known. A tensile overload will delay or retard subsequent fatigue crack growth below that expected for the case of no overload. Any crack growth analysis that does not account for this load interaction will predict an overly conservative crack growth life.

The Wheeler model was one of the first attempts to quantify fatigue crack retardation (Ref 1). The biggest drawback to this model is the empirical "shaping exponent", m. Forcing the exponent m to be a constant may provide a good correlation between the model and a particular set of experimental data, but an important loss of generality is incurred. This report proposes a modification to the Wheeler model which allows the model to be used without reliance on data fitting and without the subsequent limiting to a specific set of loading parameters.

II MODEL DEVELOPMENT

Gallagher (Ref 2) presented the Wheeler model in the following stress intensity format:

$$\frac{da}{dN} = \begin{cases} C \quad (\Delta K_{eff})^{n} & , K_{max} < K_{OL} \left[1 - \frac{\Delta a}{z_{OL}} \right]^{\frac{1}{2}} \quad (1) \\ C \quad (\Delta K)^{n} & , \text{otherwise} \quad (2) \end{cases}$$

where

$$\Delta K_{eff} = \left\{ \frac{K_{max}}{K_{OL} \left[1 - \frac{\Delta a}{z_{OL}} \right]^{\frac{1}{2}}} \right\}^{\frac{2m}{n}} \left[\Delta K \right] \quad (3)$$

Experiments involving single overloads in 2024-T3 Aluminum (Ref 3) and Ti-6Al-4V Titanium alloy (Ref 4) indicate that there is a particular value, S, of K_{OL}/K_{max} such that when $K_{OL}/K_{max} \geq S$, crack arrest occurs.

For 2024-T3 (and possibly other aluminum alloys), S is about 2.3. For Ti-6Al-4V, S is about 2.8.

The limiting condition for crack arrest is $K_{OL}/K_{max} = S$. Immediately after the overload, $\Delta a = 0$. Substituting these relations into Eq. 3 yields

$$\Delta K_{eff} \text{ (at arrest)} = \left[\frac{1}{S}\right]^{\frac{2m}{n}} \left[\Delta K\right] \quad (4)$$

Gallagher (Ref 2) stated that, for the limiting case of crack arrest, the effective stress intensity range equals the threshold stress intensity range. Using this concept and the modified Wheeler formulation for ΔK_{eff} (at arrest) [Eq (4)] leads to

$$\Delta K_{th} = \left[\frac{1}{S}\right]^{\frac{2m}{n}} \left[\Delta K\right] \quad (5)$$

Solving Eq (5) for the exponent m,

$$m = \frac{\frac{n}{2} \log \left(\frac{\Delta K_{th}}{\Delta K}\right)}{\log \left[\frac{1}{S}\right]} \quad (6)$$

Thus, it is evident that the Wheeler exponent m is not a constant but depends on the material and the loading subsequent to the overload.

III DATA CORRELATION

The number of delay cycles (N_d) following a single overload has been observed for 2024-T3 (Ref 3, 5, 6), 4340 Steel (Ref 2), and Ti-6Al-4V (Ref 4, 7). A delay cycle is defined as any post-overload cycle during which the growth rate is less than that expected for the case of no overload. See Fig. 1. In the 2024-T3 and 4340 experiments, load shedding techniques were employed to obtain constant ΔK loading before and after an overload. See Fig. 2. Because of slightly different experimental techniques, the observed delay cycles in the Ti-6Al-4V experiments correspond only approximately to N_d as defined in Fig. 1.

Loading parameters and observed delay cycles from References 2 through 7 are summarized in Table I. Eq (1) in conjunction with Eq (6) has been used in a numerical integration routine to predict the number of observed delay cycles for the various sets of loading parameters in Table I. Fig. 3 shows the correlation between predictions (N_p) and actual data (N_d).

The arrest factors S for 2024-T3, 4340, and Ti-6Al-4V were assumed to be 2.3, 2.3, and 2.8, respectively. Table II summarizes the growth rate constants, C and n, that were used for the various materials and R ratios. These constants were determined by a least squares fit to da/dN versus ΔK data presented in References 2 through 7, or, where applicable, the constants were taken directly from these references. Threshold stress intensity ranges for 2024-T3, 4340, and Ti-6Al-4V were assumed to be 2, 6, and 6 ksi $\sqrt{in}$, respectively.

For both 2024-T3 and 4340, the overload interaction zone was assumed to be equal to the radius of the plane stress plastic zone,

$$z_{OL} = \alpha \left[\frac{K_{OL}}{\sigma_{ys}} \right]^2 \tag{7}$$

where

$$\alpha = \frac{1}{2\Pi}$$

However, α and hence z_{OL} most likely depend on material type and thickness. Wei et al. (Ref 4) presented data indicating that the overload interaction zone in Ti-6Al-4V is several times the value calculated using Eq (7). Accordingly, the predictions for Ti-6Al-4V were made assuming the overload interaction zone to be approximately four times the plane stress plastic zone radius ($\alpha = \frac{4}{2\Pi}$).

As evident from Fig. 3, the Wheeler model as modified in this report can predict delay cycles following a single overload in 2024-T3, 4340, and Ti-6AL-4V within essentially a factor of two of the actual experimental data. For all cases considered, the exponent m varied from 1.07 to 4.34 according to Eq (6).

The model at present appears to have the basic elements necessary for a generalized crack growth analysis, and its success in predicting delay cycles is encouraging. Further refinements are being made toward the ultimate goal of predicting crack growth under a general load spectrum.

REFERENCES

1. Wheeler, O. E., "Crack Growth Under Spectrum Loading." General Dynamics Report FZM-5602, 30 June 1970.
2. Gallagher, J. P. and T. F. Hughes, "The Influence of Yield Strength on Crack Growth Rate Delay in 4340 Steel." AFFDL-TR-73-XXX, September 1973. (To be published.)
3. Probst, E. and B. Hillberry, "Fatigue Crack Delay and Arrest Due to Single Peak Tensile Overloads." Presented at the AIAA Dynamics Specialists Conference, Williamsburg, Virginia, March 19-20, 1973.
4. Wei, R., T. Shih, and J. Fitzgerald, "Load Interaction Effects on Fatigue Crack Growth in Ti-6Al-4V Alloy." NASA CR-2239, April 1973.
5. Von Euw, E., R. Hertzberg, and R. Roberts, "Delay Effects in Fatigue Crack Propagation." ASTM STP 513, 1972, pp. 230-259.
6. Trebules, V., R. Roberts, and R. Hertzberg, "Effect of Multiple Overloads on Fatigue Crack Propagation in 2024-T3 Aluminum Alloy." ASTM STP 536, 1973, pp. 115-146.
7. Jones, R. E., "Fatigue Crack Growth Retardation After Single-Cycle Peak Overload in Ti-6Al-4V Titanium Alloy." AFML-TR-72-163, April 1972.

TABLE I

Single Overload Delay Data

Material	Reference	R	K_{max} (ksi$\sqrt{in}$)	K_{OL} (ksi$\sqrt{in}$)	$\frac{K_{OL}}{K_{max}}$	N_d (Cycles)
2024-T3	3	0.3	6.8	13.7	2.01	120,000
			9.9	17.1	1.73	35,000
				20.4	2.06	87,500
				21.5	2.17	104,000
			12.2	19.5	1.60	36,000
				23.7	1.94	107,000
				26.5	2.17	246,000
			14.4	22.3	1.55	9,500
				30.6	2.13	398,800
				32.4	2.25	278,500
			16.7	27.8	1.66	21,000
				35.9	2.15	244,000
	5	0.29	12.6	26.1	2.07	332,000
			21.0	28.5	1.36	5,000 *
				36.0	1.71	52,200 *
		0.1	8.2	12.5	1.52	10,000
				14.9	1.82	32,000
				17.1	2.09	50,000 *

* Average

TABLE I (CONTINUED)

Single Overload Delay Data

Material	Reference	R	K_{max} (ksi $\sqrt{in}$)	K_{OL} (ksi$\sqrt{in}$)	$\frac{K_{OL}}{K_{max}}$	N_d (Cycles)
2024-T3	5	0	13.7	21.2	1.55	9,000
				28.5	2.08	72,000
			15.0	30.0	2.00	98,000
			18.0	27.0	1.50	13,000
				31.5	1.75	33,000
				36.0	2.00	113,000
			21.0	31.5	1.50	14,000
				36.8	1.75	63,000
				42.0	2.00	258,000
	6	0.05	15.8	23.2	1.47	5,000 *
		0.29	21.0	28.6	1.36	4,800 *
		0.67	45.0	52.4	1.16	5,400
4340, σ_{ys} =120 ksi	2	0.1	20.0	40.0	2.00	35,000 *
4340, σ_{ys} = 220 ksi	2	0.1	20.0	40.0	2.00	4,000 *
Ti-6Al-4V	4	0	14.0	21.0	1.50	2,000
				28.0	2.00	7,500

* Average

TABLE I (CONTINUED)

Single Overload Delay Data

Material	Reference	R	K_{max} (ksi $\sqrt{in}$)	K_{OL} (ksi $\sqrt{in}$)	$\frac{K_{OL}}{K_{max}}$	N_d (Cycles)
Ti-6Al-4V	4	0	14.0	31.3	2.24	15,000
				33.0	2.36	25,000
				33.6	2.40	30,500
				34.3	2.45	44,500
	7	0.1	18.5	31.5	1.70	8,200
				37.0	2.00	11,200
			28.0	42.0	1.50	2,400
			19.3	38.6	2.00	10,100
			28.7	43.1	1.50	2,500

TABLE II

CRACK GROWTH RATE CONSTANTS

$$\frac{da}{dN}\text{, in/cyc} = C\ [\Delta K\text{, ksi}\sqrt{\text{in}}]^n$$

Material	Reference	R	C	n
2024-T3	3,5,6	0.3	1.48×10^{-9}	3.59
2024-T3	5,6	0	8.66×10^{-9}	2.68
2024-T3	6	0.67	3.21×10^{-9}	3.27
4340, σ_{ys} = 120 ksi	2	0.1	1.38×10^{-10}	3.20
4340, σ_{ys} = 220 ksi	2	0.1	3.46×10^{-10}	3.20
Ti-6Al-4V	4*	0	5.18×10^{-9}	2.60
Ti-6Al-4V	7**	0.1	8.85×10^{-9}	2.48

* ΔK 14 $\geq$ ksi $\sqrt{\text{in}}$

** ΔK 18 $\geq$ ksi $\sqrt{\text{in}}$

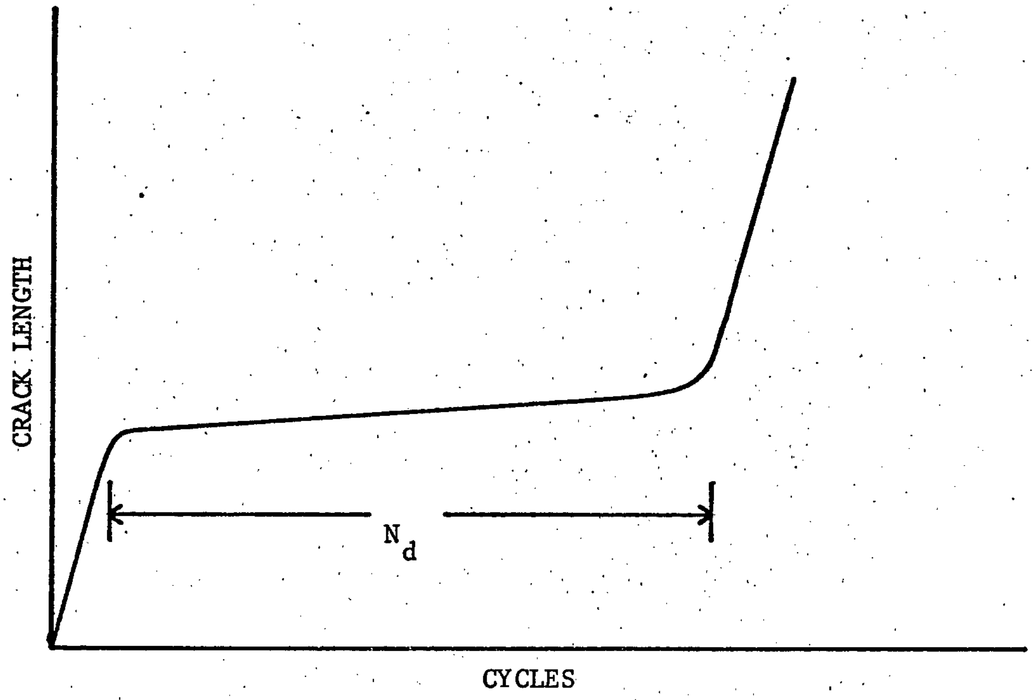

FIG. 1. DELAY CYCLES

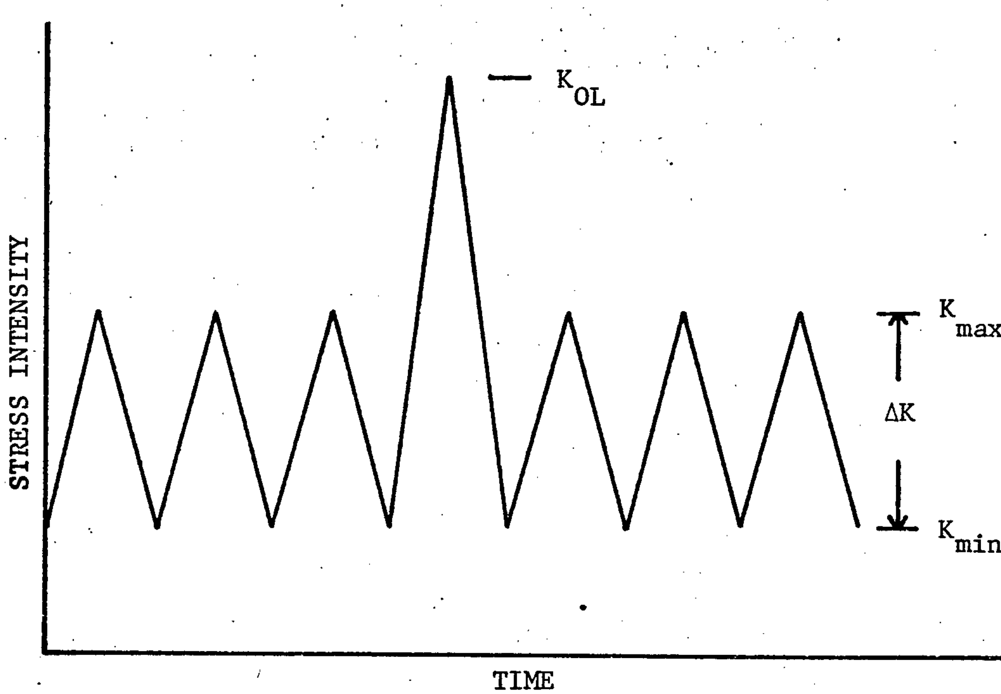

FIG. 2. APPLIED LOADING.

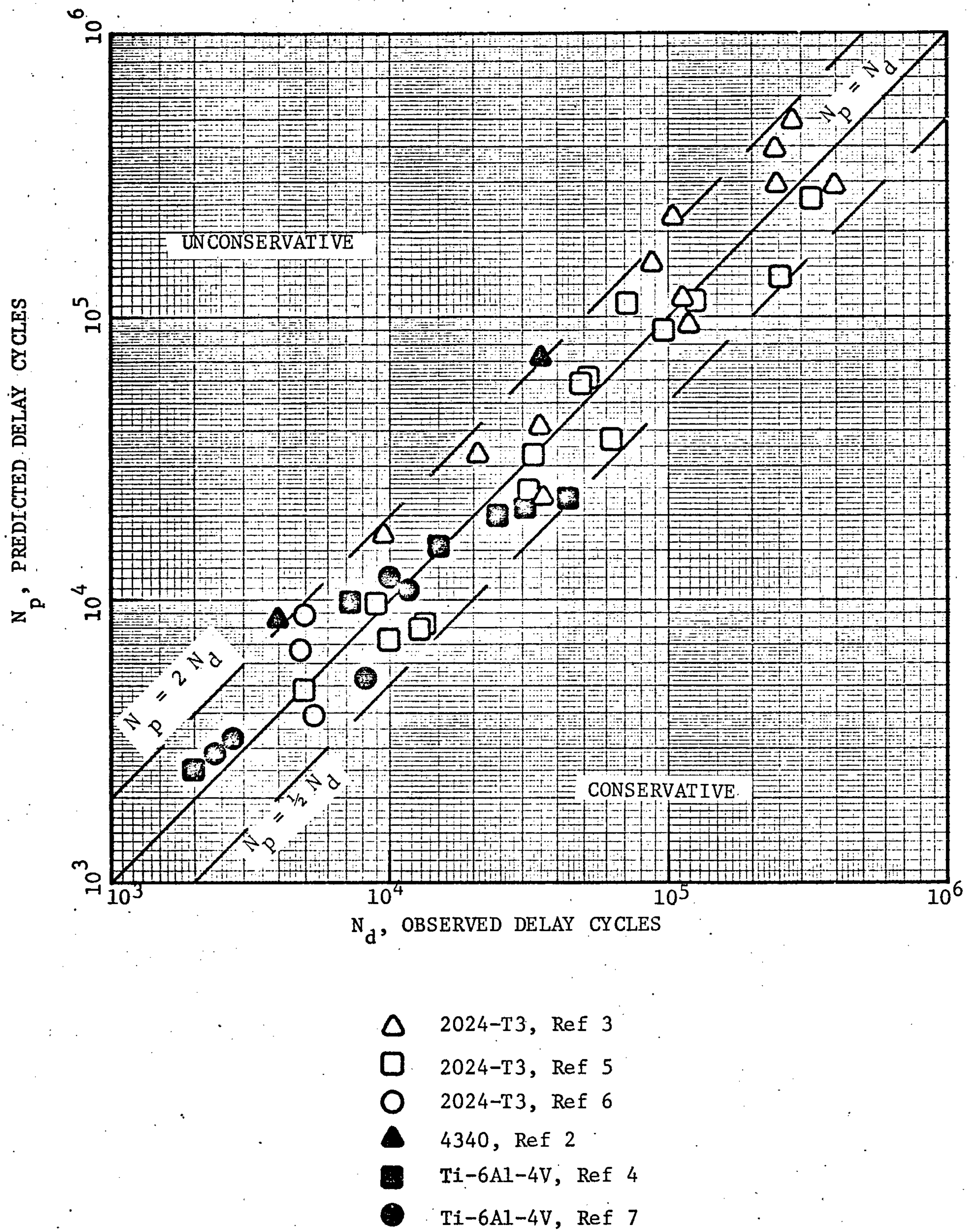

FIG. 3. PREDICTED DELAY CYCLES VERSUS OBSERVED DELAY CYCLES.